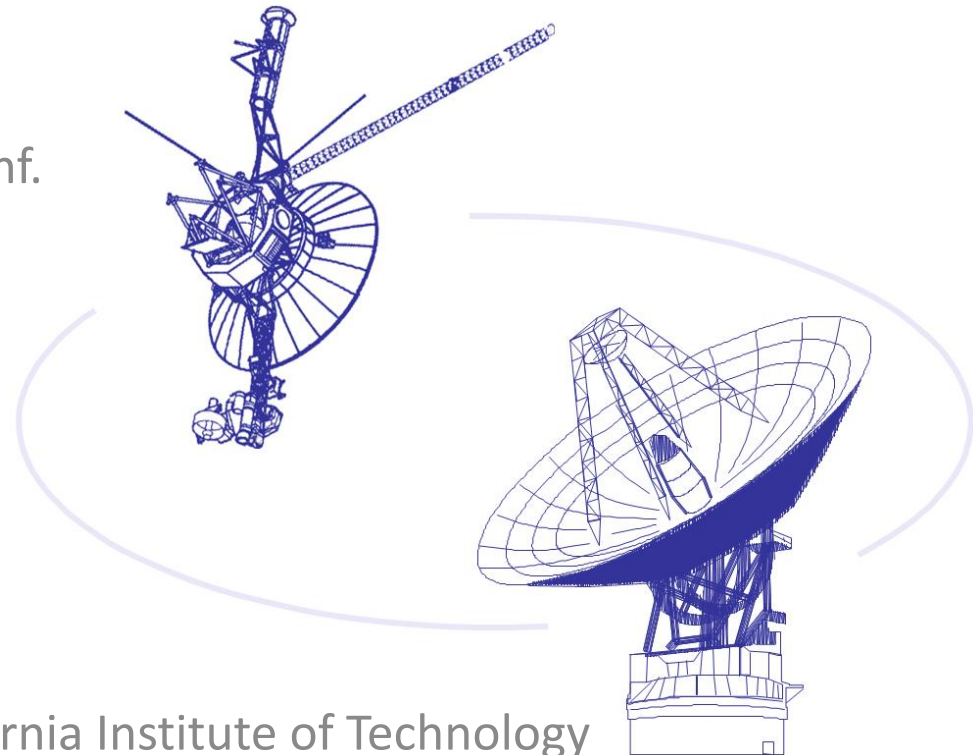


# CubeSat Telecom System Needs for Deep-Space Missions

2017 Interplanetary Small Satellite Conf.  
San Jose, California, USA  
1-2 May 2017



M. Michael Kobayashi

Jet Propulsion Laboratory at the California Institute of Technology

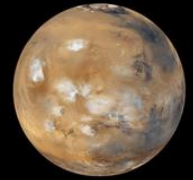
- Deep-Space telecom needs
- Survey of CubeSat communication systems
- Overcoming large distances
- Navigation in deep space
- Iris Deep-Space Transponder
- Iris hardware design description
- Software Defined Radio heritage
- Comparison of deep-space transponders
- Planned deep-space CubeSat missions
- Future enhancements

# Deep-Space Telecom Needs



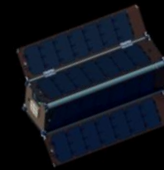
## Trajectory

Large free-space path loss  
Spacecraft dynamics effects



## Navigation

Outside GPS signal range  
No Earth's magnetic fields



## Environment

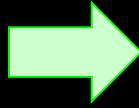
High ionizing radiation  
Clock stability over mission duration

# Deep-Space Telecom Needs



## Trajectory

Large free-space path loss  
Spacecraft dynamics effects

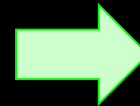


Large aperture antennas  
Low receiver sensitivity

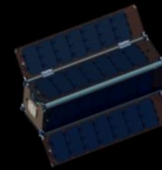


## Navigation

Outside GPS signal range  
No Earth's magnetic fields



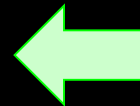
Radiometric Navigation  
Techniques



## Environment

High ionizing radiation  
Clock stability over mission duration

Space-grade parts  
Coherent Transponder

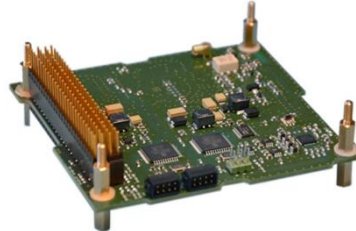


An equally capable ground station to support deep-space exploration needs is required.

# Survey of CubeSat Telecom Systems



**AstroDev Li-1**



**ISIS TRXUV**



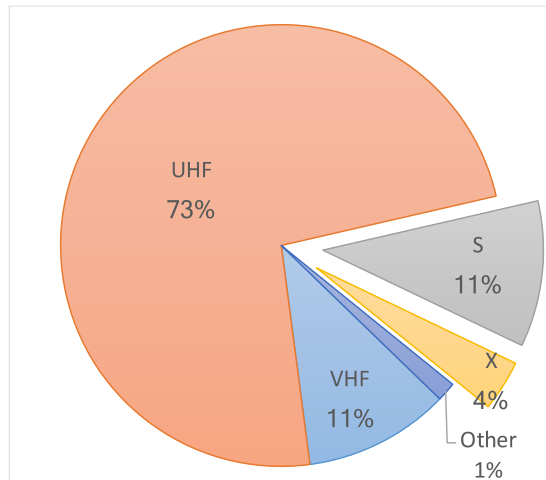
**GomSpace AX100**



**Freewave FGRM**

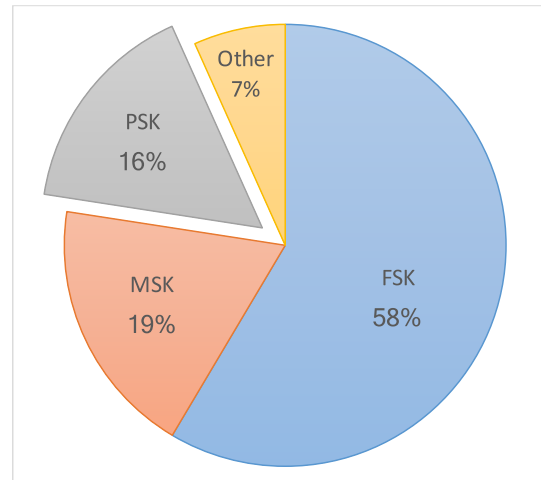
	AstroDev Li-1	ISIS TRXUV	GomSpace AX100	Freewave FGRM
Bands	VHF/UHF	VHF/UHF	VHF/UHF	S-band
Mod	FSK/GMSK	BPSK	FSK/MSK/GFSK/GMSK	GFSK
Rates (baud)	9600	1200 – 9600	100 – 115,200	115,200 – 153,600

**Frequency Bands**



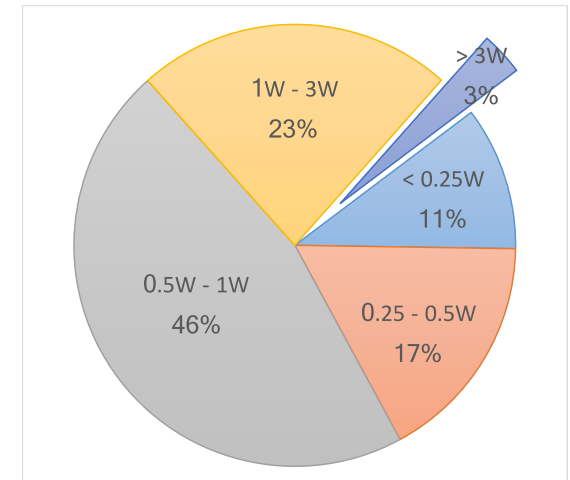
Deep-space frequency band limited to S, X, and Ka

**Modulation Schemes**



PSK highly recommended by CCSDS for deep-space use

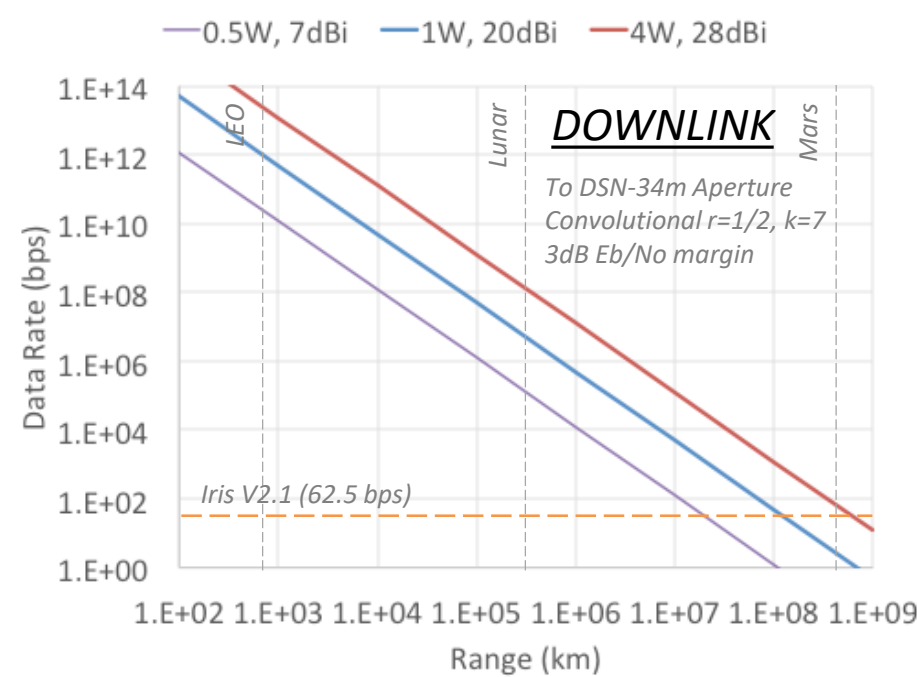
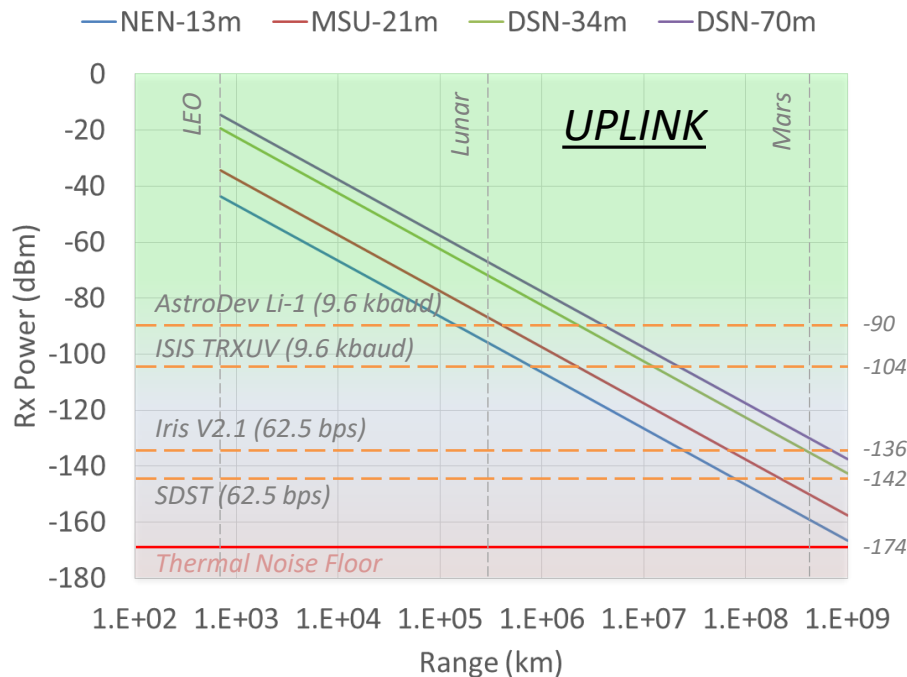
**RF Output Power**



Higher power for farther distances necessary

\* Data Source: B. Klofas, CubeSat Communications System Table, Version 13, 16 Aug 2016.

# Overcoming Large Distances

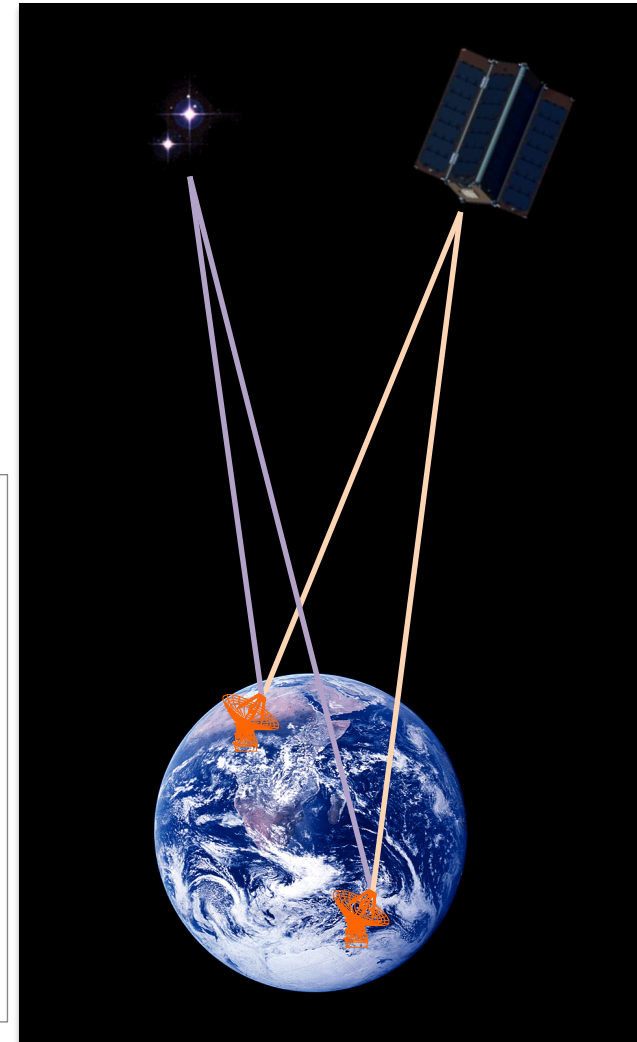
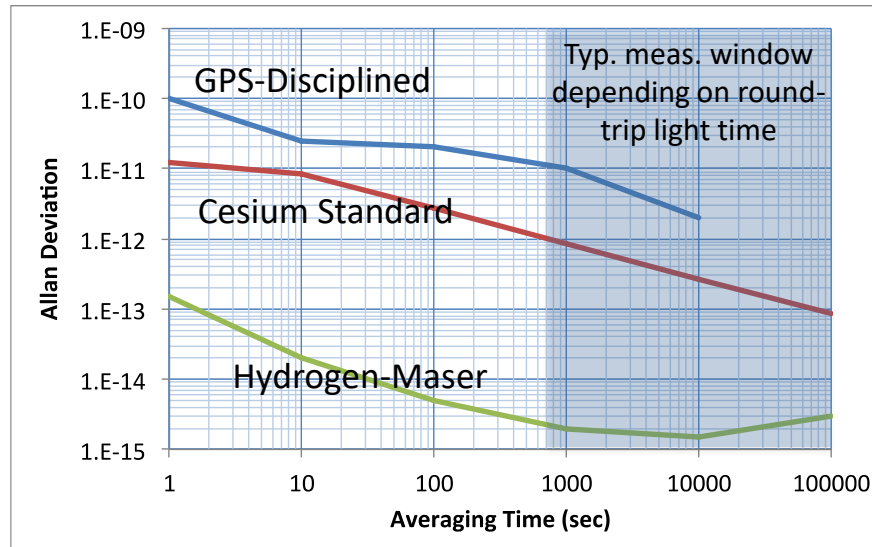


# Navigation in Deep Space



- Support radiometric navigation (ranging, Doppler track, VLBI) for orbit determination
  - A carefully characterized Coherent Radio Transponder is necessary for turn-around ranging on the S/C
  - Transmitter with special DOR tones for VLBI support (note: need two Earth stations to support)
  - Earth Station equipped with navigation processing tools
- Stable reference clock for reduced navigational error
  - Detect milli-Hertz variations within GHz signals.
  - Long integration times with low frequency drift
    - Stability required over round-trip light time (ranging)
    - VLBI tracking times 8-12 hours.
- Overcome S/C dynamic effects
  - Configurable carrier tracking loops for varying dynamics
  - Pre-emphasis Doppler compensation from Earth station

$$20 \log_{10} \left( \frac{f_{link}}{f_{ref}} \right)$$



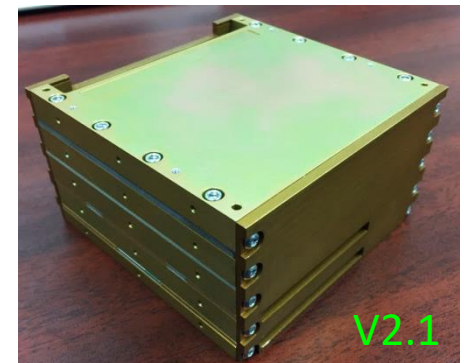
# Iris Deep-Space Transponder



- CubeSat/SmallSat compatible deep-space transponder
- ~0.5U volume (100.5 x 101.0 x 56.0 mm; transponder only)
- DSN/NEN-compatible X-band uplink/downlink (7.2GHz/8.4GHz)
- Software Defined Radio with Leon3-FT softcore processor
- Provides navigational support (Doppler, Ranging, DDOR)
- Modular hardware design for other frequency bands (UHF, S-band, Ka-band)



Iris Specification	Units	Iris V1.0 for INSPIRE	Iris V2.0 for MarCO	Iris V2.1 for SLS EM-1
Mass	grams	450 (no chassis)	1210 (w/ UHF-Rx)	< 1000 (X/X-only)
Volume	U	0.46	0.77 (w/ UHF-Rx)	0.56
Bus Input Voltage	Vdc	6.4 – 8.4	10.5 – 12.3	9.0 – 28.0
DC Power*	W	13.0	35.0	33.7
RF Output Power*	W	0.15	3.3	3.8
Receiver Noise Figure	dB	5.0 – 6.0	3.5	3.5
Receiver Sensitivity	dBm	-135 @ 70Hz LBW	-139 @ 70Hz LBW	-151 @ 20Hz LBW
Uplink Data Rate†	bps	1,000	62.5 & 1,000	62.5 – 8,000
Downlink Data Rate†	bps	62.5 – 64,000	62.5 & 1,000 & 8,000	62.5 – 256,000
Telemetry Encoding		Conv & Reed Solomon	Turbo-1/6 only	Conv, Reed Solomon, Turbo 1/2, 1/3, 1/6
Radiation Tolerance	krads	N/A	15.0 TID	23.0 TID
S/C Interface		1 MHz SPI	1 MHz SPI	1 MHz SPI



\* Nominal at ambient

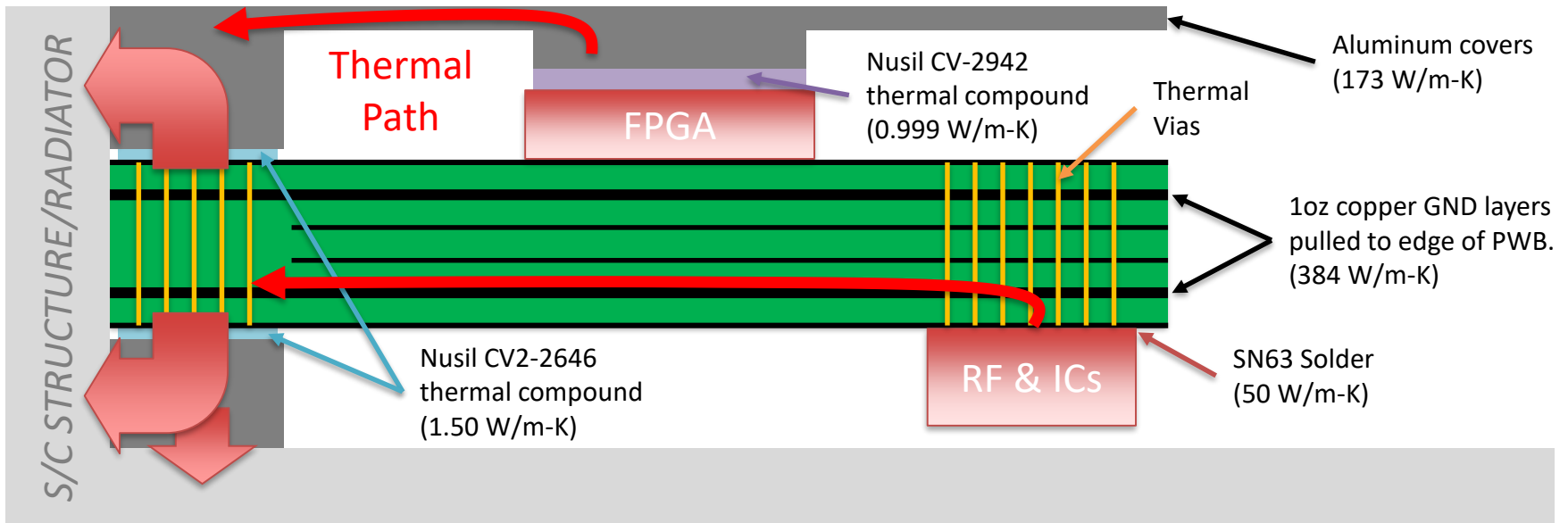
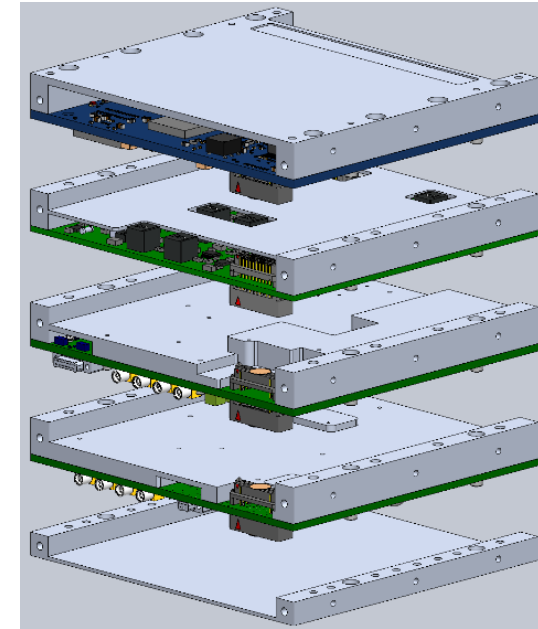
† Subject to link margin

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# Hardware Design Considerations



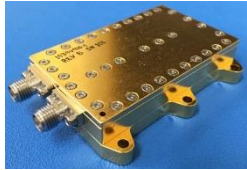
- Modular hardware built of slice elements
  - NASA-STD-4009 (Space Telecom Radio System) guidelines
  - Slices are interconnected with stacking connectors
  - RF modules are generic to allow future designs with other frequency bands (UHF, S, Ka)
- Radiation tolerant up to 23 krads; no destructive SEL.
- EMI covers/shields to minimize radiated emissions
- Emphasized efficient thermal design



# Top-Level Block Diagram

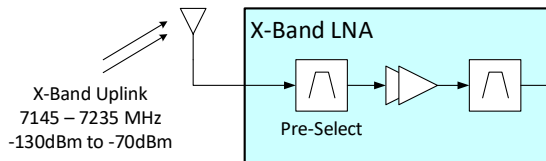


## Iris LNA



Modular MIC assembly

- Reduce noise figure by shortening cable length from antenna
- Separate gain cavities between LNA and Rx (risk of oscillations)

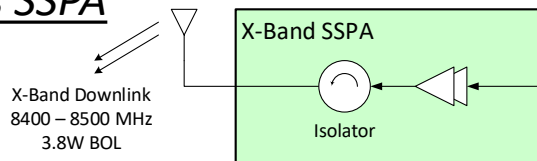


## Iris SSPA

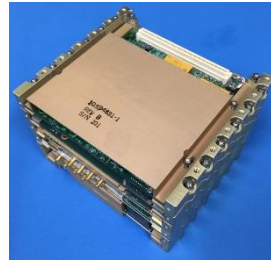


Modular MIC assembly

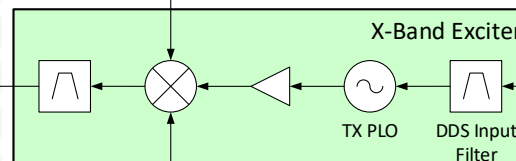
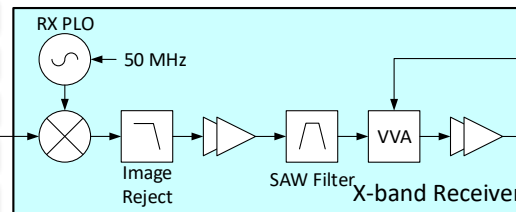
- Provide superior heat dissipation path to structure/radiator
- Chip-and-wire assy to reduce losses for higher efficiency



## Iris Transponder Stack

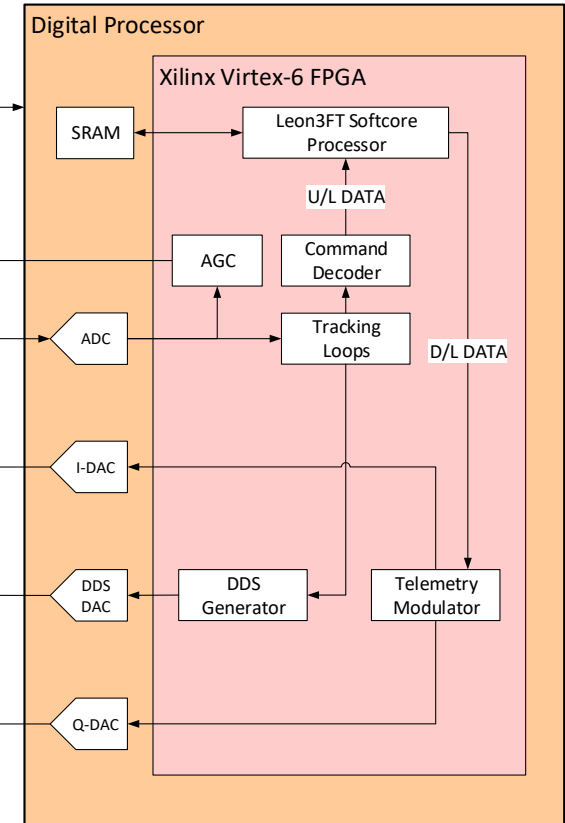


50MHz TCXO



Modular stacked-slice assembly

- Superheterodyne receiver with single-downconversion stage to 112.5 MHz IF
- Digitally closed tracking loops (carrier, subcarrier, symbol)
- Direct Digital Synthesis (DDS) reference for downlink carrier Doppler tracking
- Baseband telemetry modulated direct at X-band
- Embedded softcore processor (Leon3-FT) for configuration and protocol mgmt

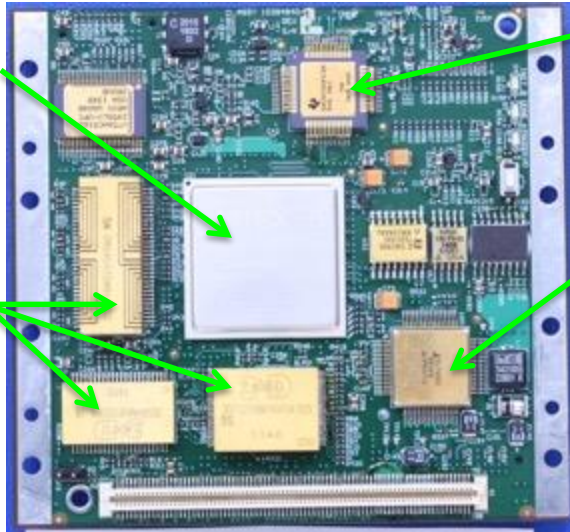


# Iris Hardware Photos

## Digital Processor

Virtex-6  
FPGA

SRAM  
FLASH



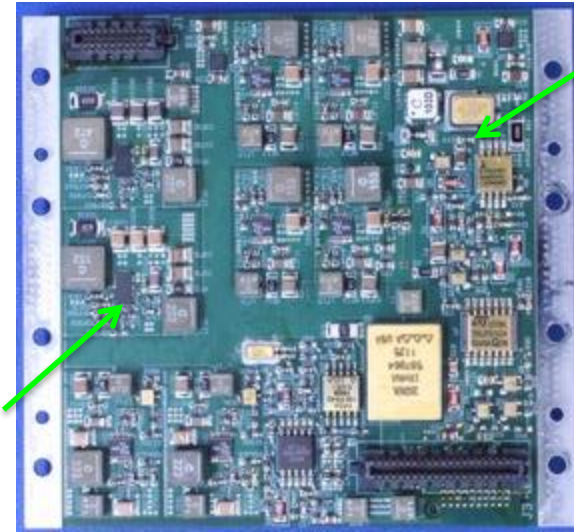
DDS  
DAC

1V  
Reg

## Power Supply

Flyback  
Conv

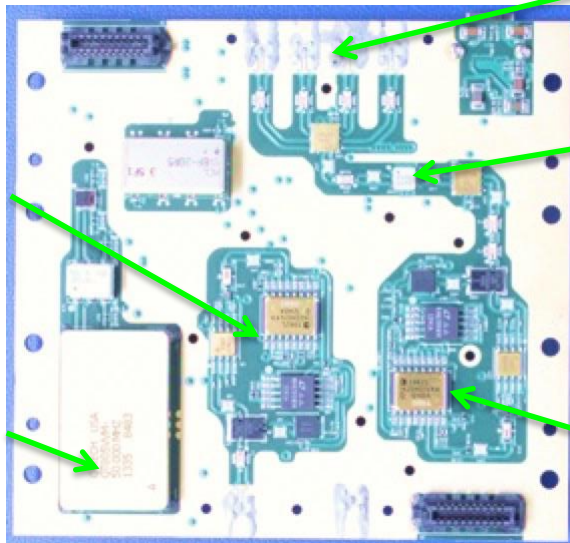
Switchers



## X-band Exciter

Rx-PLL

TCXO



Tx-Out

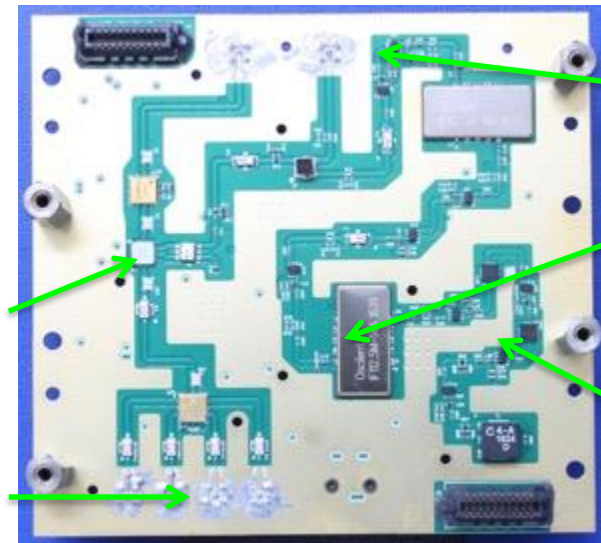
I/Q  
Mixer

Tx-PLL

## X-band Receiver

Img-Rej  
Mixer

Rx-In



IF  
Amps

SAW  
Filters

VVAs

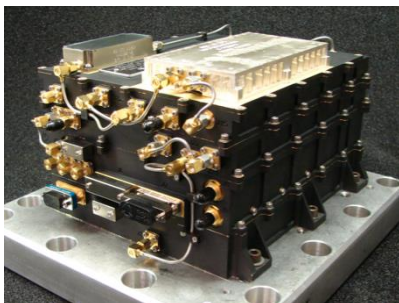
# Software Defined Radios



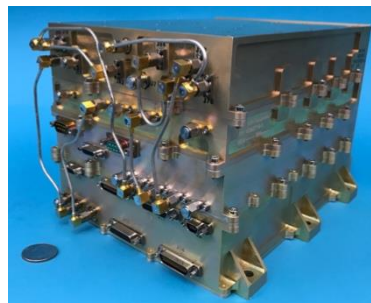
- Leading the pathway to “**smart radios**”
  - Reconfigurable to adapt to mission-specific needs
  - Platform for rapid technology infusion
    - Delay/Disruption Tolerant Networking
    - Pseudo-noise (PN) Regenerative Ranging
    - Advanced higher-order modulation schemes
    - State-of-the-art Forward Error Correction algorithms



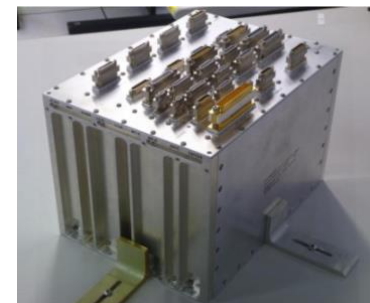
# Software Defined Radio Heritage Pieces



**Electra Proximity Radio**

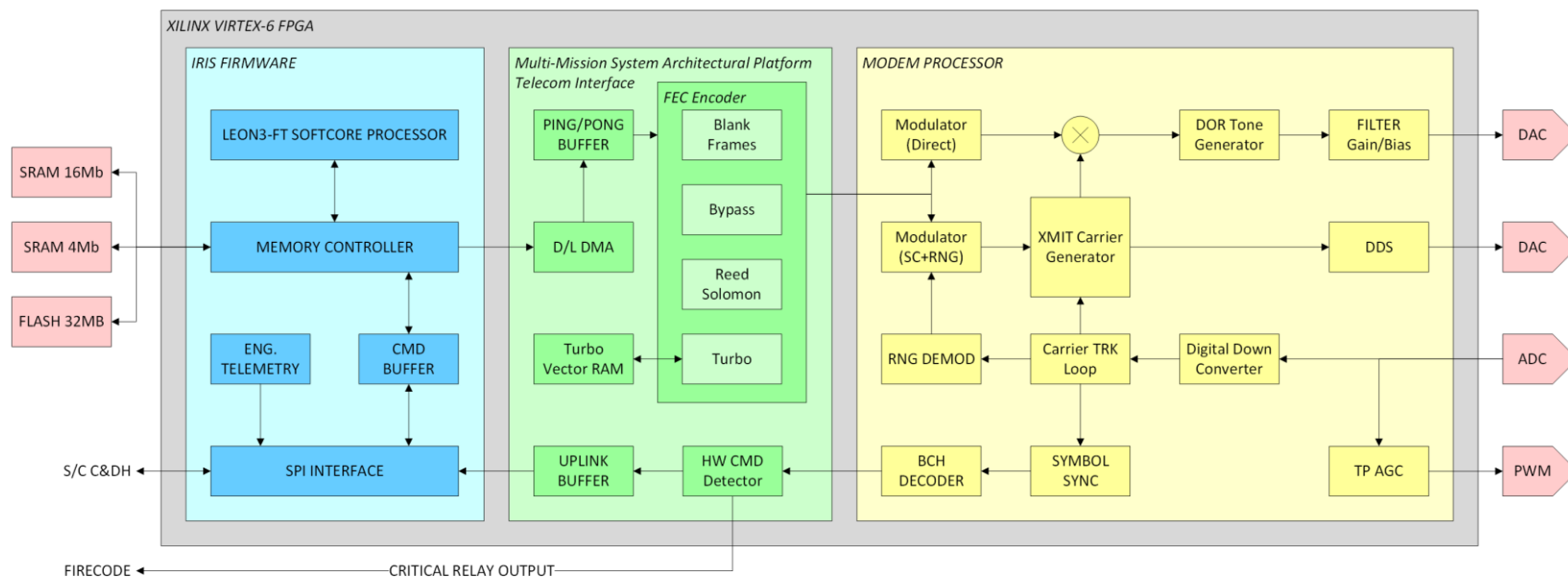


**Universal Space Transponder**



**Multi-Mission Sys. Architectural Platform**

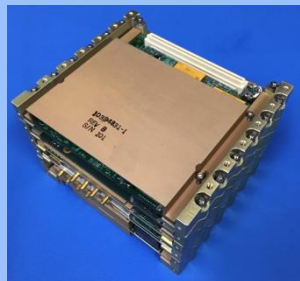
Automatic Gain Control algorithm	Coherent transponder algorithm	Reed-Solomon encoder
Carrier/Subcarrier tracking loops	Sequential ranging demodulator	Turbo 1/2, 1/3, 1/6 encoder
Phase Shift Key modem	Delta-DOR tone generator	Hardware Command Detector
Early/Late symbol synchronizer	BCH uplink decoder	Error Detection and Correction



# Deep-Space Transponder Comparisons



Iris (JPL)



Mass: 1.0 kg

UST (JPL)



Mass: 4.5 kg<sup>†</sup>

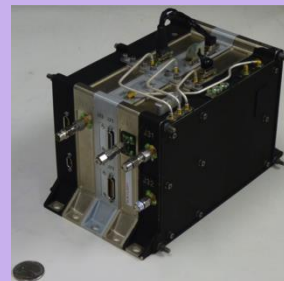
Reconfigurable

SDST (GD)



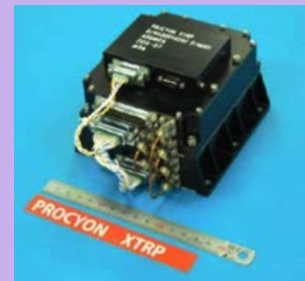
Mass: 3.3 kg

Frontier (APL)



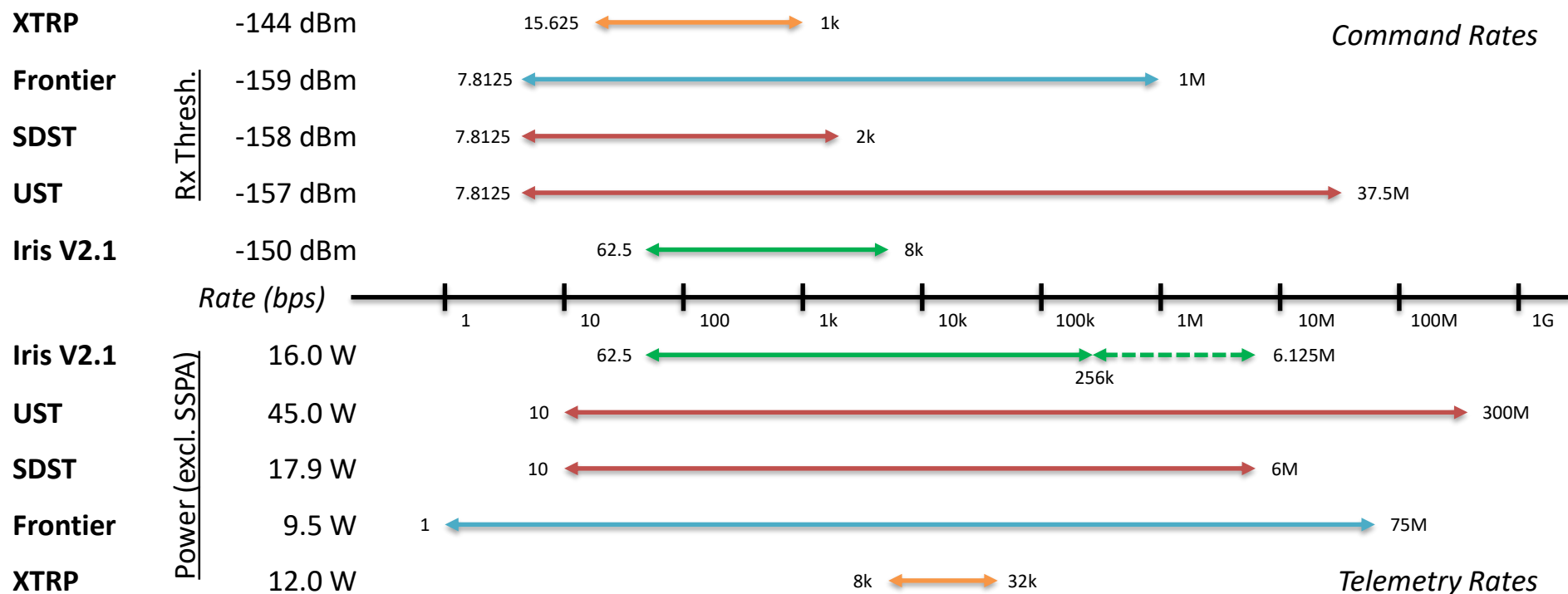
Mass: 2.3 kg

XTRP (JAXA)

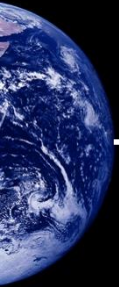


Mass: 1.2 kg

One-Time Programmable



# Planned Deep-Space CubeSat Missions



1.5 Mkm

15 Mkm

84 Mkm

110 Mkm

160 Mkm

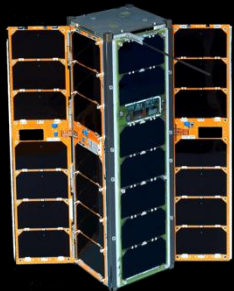
0.01 AU

0.10 AU

0.56 AU

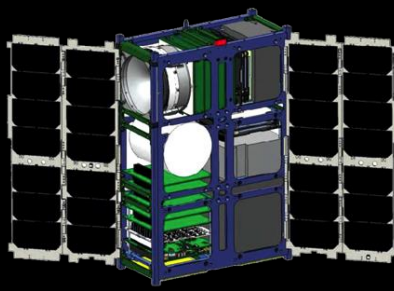
0.74 AU

1.07 AU



INSPIRE, JPL

Provide reduced size and cost components to enable a new class of interplanetary explorers.



CuSP, SwRI

Study the dynamic particles and magnetic fields that stream from the Sun and as a proof of concept for the feasibility of a network of stations to track space weather.



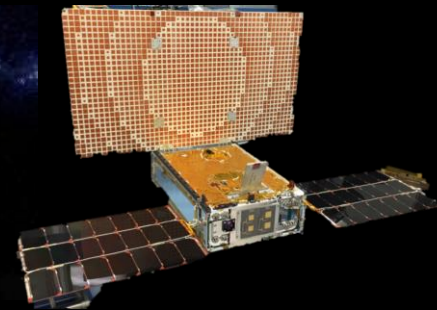
BioSentinel, AMES

Use yeast to detect, measure & compare the impact of deep space radiation on living organism over long durations beyond low-Earth orbit.



NEA Scout, MSFC

Proof-of-concept of a solar sail CubeSat capable of encountering near-Earth asteroids (NEA).



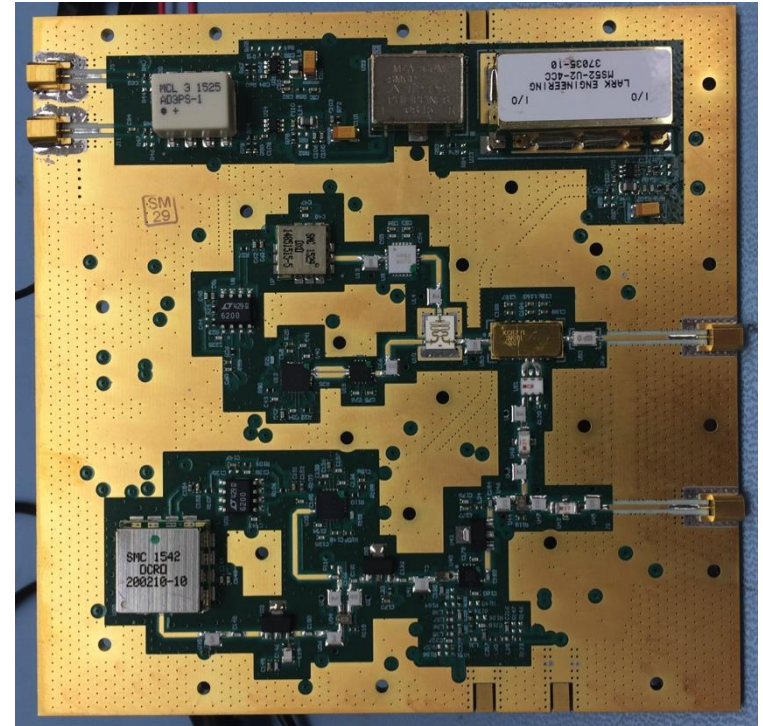
MarCO, JPL

Provide real-time bent-pipe relay communications during InSight's Entry-Descent-Landing into Mars

# Future Enhanced Iris Capabilities



- Higher downlink rates beyond 2Mbps
- Low-Density Parity-Check (LDPC) code
- SpaceWire interface for high-rate data transfers to S/C C&DH unit
- Pseudonoise (PN) Regenerative Ranging for improved ranging SNR
- Reliable space-link protocols (CCSDS Prox-1 protocol)
- Delay/Disruption Tolerant Networking
- Other frequency bands (UHF, S, Ka)



## TRL-4 S-/Ka-band exciter

S-band RF output: 0dBm

S-band phase noise: -95 dBc/Hz

Ka-band RF output: -13dBm

Ka-band phase noise: -74 dBc/Hz

Power: 4.7W

- Iris Deep-Space Transponder with radiometric tracking support for orbit determination of CubeSats.
- NASA's Deep Space Network functions for overcoming the challenges of deep-space telecom and navigation.
- Software defined radios as “smart radios” to enable rapid technology infusion.



**Jet Propulsion Laboratory**  
California Institute of Technology

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[jpl.nasa.gov](http://jpl.nasa.gov)